Environmental Conditions Responsible for Solar Activity

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Solar coronal activity is of concern to the Air Force primarily because of the terrestrial effects of coronal mass ejections and solar flares. Coronal mass ejections can lead to geomagnetic disturbances that in turn cause magnetospheric substorms. This geomagnetic activity disturbs the ionosphere, especially in the polar regions, interfering with radio propagation. Ionizing radiation (UV and X-ray) and particle events from solar flares can also lead to ionospheric disturbances. Furthermore, major flares pose serious hazards to astronauts.

During the past three years, the Stanford group has obtained significant theoretical insights into the driving mechanism of eruptive events in the solar corona. The question of what causes coronal eruptions inevitably leads to questions concerning the plasma conditions and magnetic field configurations in which eruptions occur. In particular, we have grappled with the long-standing issue of how the coronal plasma is maintained at a temperature of several million degrees, while the underlying surface of the Sun that is visible in white light has a temperature of only a few thousand degrees.

Our work over the past three years has taken us closer to the goal of being able to predict the imminent onset of solar flares and coronal mass ejections.

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1. Introduction

Solar coronal activity is of concern to the Air Force primarily because of the terrestrial effects of coronal mass ejections and solar flares. Coronal mass ejections can lead to geomagnetic disturbances that in turn cause magnetospheric substorms. This geomagnetic activity disturbs the ionosphere, especially in the polar regions, interfering with radio propagation. Ionizing radiation (UV and X-ray) and particle events from solar flares can also lead to ionospheric disturbances. Furthermore, major flares pose serious hazards to astronauts.

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Our work over the past three years has taken us closer to the goal of being able to predict the imminent onset of solar flares and coronal mass ejections.

2. Mechanism of coronal eruptions

Essentially all of the activity observed in the Sun's corona is related to the presence of the magnetic field that permeates the solar atmosphere. Since the forces due to gas pressure are very small in the corona, coronal magnetic field configurations must be essentially force-free, meaning that the electric current must flow almost parallel to the magnetic field at each point in the corona. Magnetic free energy is stored when photospheric shearing and twisting motions displace the footpoints of the coronal magnetic field. This basic scenario has been accepted for decades, but the details of how magnetic free energy is built up and then suddenly released have remained a puzzle. One of our key accomplishments has been an improved understanding of the eruption of coronal magnetic fields.

The most impressive coronal eruptive phenomenon is the coronal mass ejection. Before it erupts, a coronal mass ejection has the appearance of a huge dome of plasma which expands over several days. Then suddenly, the coronal mass ejection is unleashed, flinging plasma and magnetic field out to great distances from the Sun. It appears likely that the eruption of coronal magnetic fields is a basic process, occurring on many different spatial scales.

Roumeliotis, Sturrock & Antiochos (1993) performed a numerical study using the Cray X-MP at NRL to follow the evolution of a force-free coronal magnetic field as increasing footpoint displacements are applied at the photosphere. For these calculations, we assumed that an initially potential dipole magnetic field is buried within the Sun. Motions that are latitude-dependent and anti-symmetric about the equator are then applied at the photosphere. The angular positions of the magnetic footpoints at the solar surface are smoothly increased according to a fixed velocity profile which vanishes at the equator and the poles. The idealized physical model is illustrated in Figure 1 (a). As the footpoint displacements at the solar surface are progressively increased, the coronal magnetic field expands outwards. But it does not expand uniformly. This can be seen by tracking the height of a specific field line as a function of the maximum angular displacement at the photosphere, as shown in Figure 1 (b). The height increases steadily until the maximum angular displacement approaches a critical value. Past this critical value, the height of the field line increases dramatically even for tiny changes in footpoint positions. We propose that this qualitative change in the behavior of sheared, expanding magnetic configurations corresponds to the onset of eruption in coronal magnetic structures.

Sturrock (1993), and Sturrock, Antiochos & Roumeliotis (1993) have developed an analytic theory for force-free fields stressed by progressive footpoint motions. This analytic theory yields formulas for the expansion and energy content of the coronal field that are in excellent agreement with the results of our detailed numerical computations.

We are presently making the computational model more realistic by incorporating the effects of finite gas pressure and gravity. These modifications will allow us to simulate the eruption of coronal mass ejections beyond the lift-off stage. We are also continuing computational and analytical studies to understand the sudden transition to a regime characterized by sensitive dependence on boundary conditions.

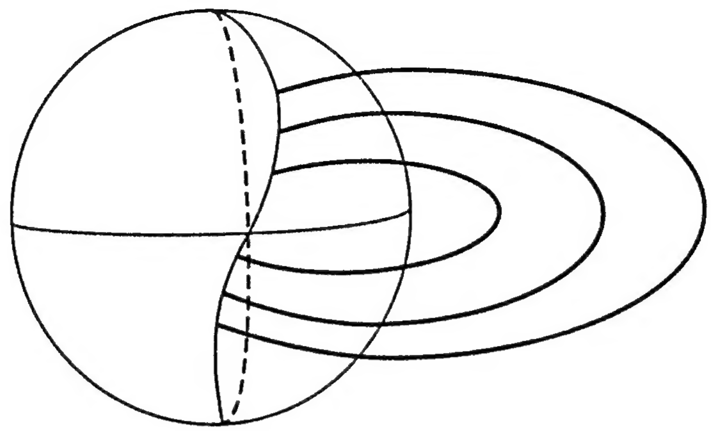

Figure 1(a)

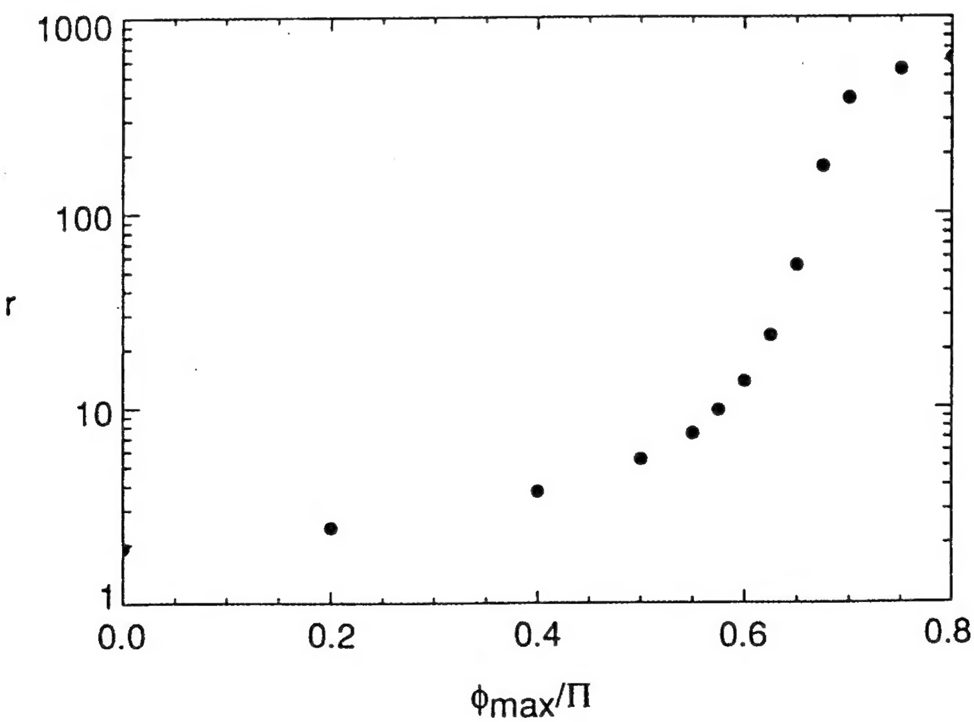

Figure 1(b)

3. Reconstruction of coronal magnetic fields

One of the main impediments to an improved theoretical understanding of solar flares and eruptive phenomena is the fact that the coronal magnetic field cannot be directly observed. The spectroscopic effects that permit the observation of the vector magnetic field at the level of the photosphere cannot be used to determine the field at higher levels.

Roumeliotis (1994) has devised a method for reconstructing the coronal magnetic field above an active region using vector magnetic field measurements at the photosphere, together with the assumption that the coronal field is essentially force-free. The computation begins with the potential field that matches the vertical component of the field at the photosphere, and then proceeds to systematically adjust the coronal configuration until the computed field is force-free and matches the observed vertical and transverse components of the field at the photosphere. An example of how this method works on actual magnetograph data is shown in the following diagrams, which present the view from directly above the active region. Figure 2(a) shows the potential field lines in the vicinity of a magnetic neutral line, where the line-of-sight photospheric magnetic field changes sign. Figure 2(b) shows the corresponding field lines of the reconstructed force-free field. A striking feature of the reconstructed coronal magnetic field is the dramatically different connectivity of the field lines. Also, the force-free field is strongly sheared near the neutral line - a feature commonly associated with pre-flare active regions. Figure 2(c) shows the same active region as seen in X-rays. There is good overall agreement between the reconstructed magnetic field lines and the location of bright X-ray structures.

An important issue in the interpretation and use of photospheric vector magnetograms is the nature of the observational errors. Klimchuk and Canfield (1993) studied the influence of vector magnetograph measurement errors on the inferred properties of coronal magnetic fields. They set limits on the accuracy with which the coronal field can be known, given the uncertainties of the vector magnetograph data.

Our empirical studies of coronal force-free fields are continuing. In collaboration with our observer colleagues at the National Solar Observatory at Sacramento Peak, we are exploring such basic issues as the relationship between active region magnetic fields and solar flares. In particular, we are investigating whether the coronal magnetic field configuration can provide early warning of imminent flare activity.

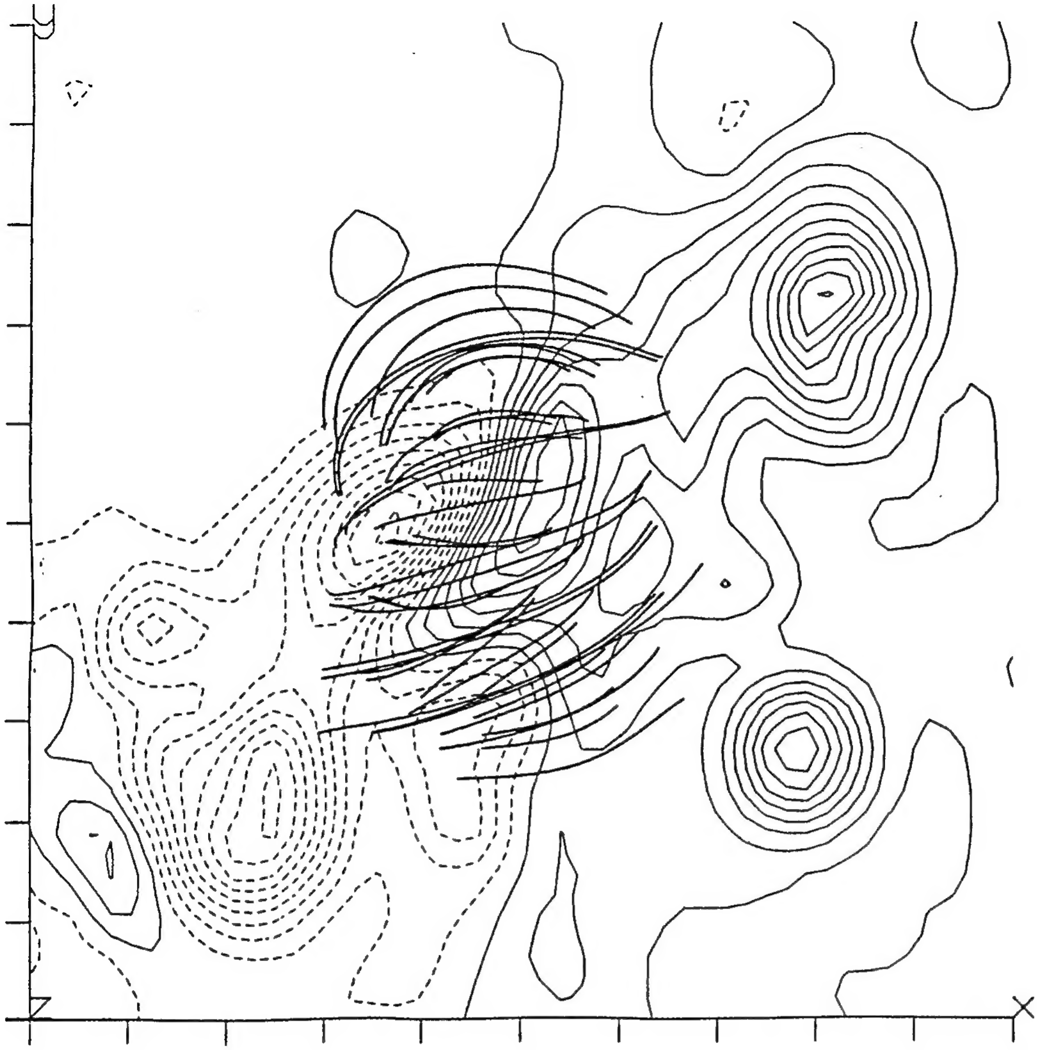

Figure 2(a)

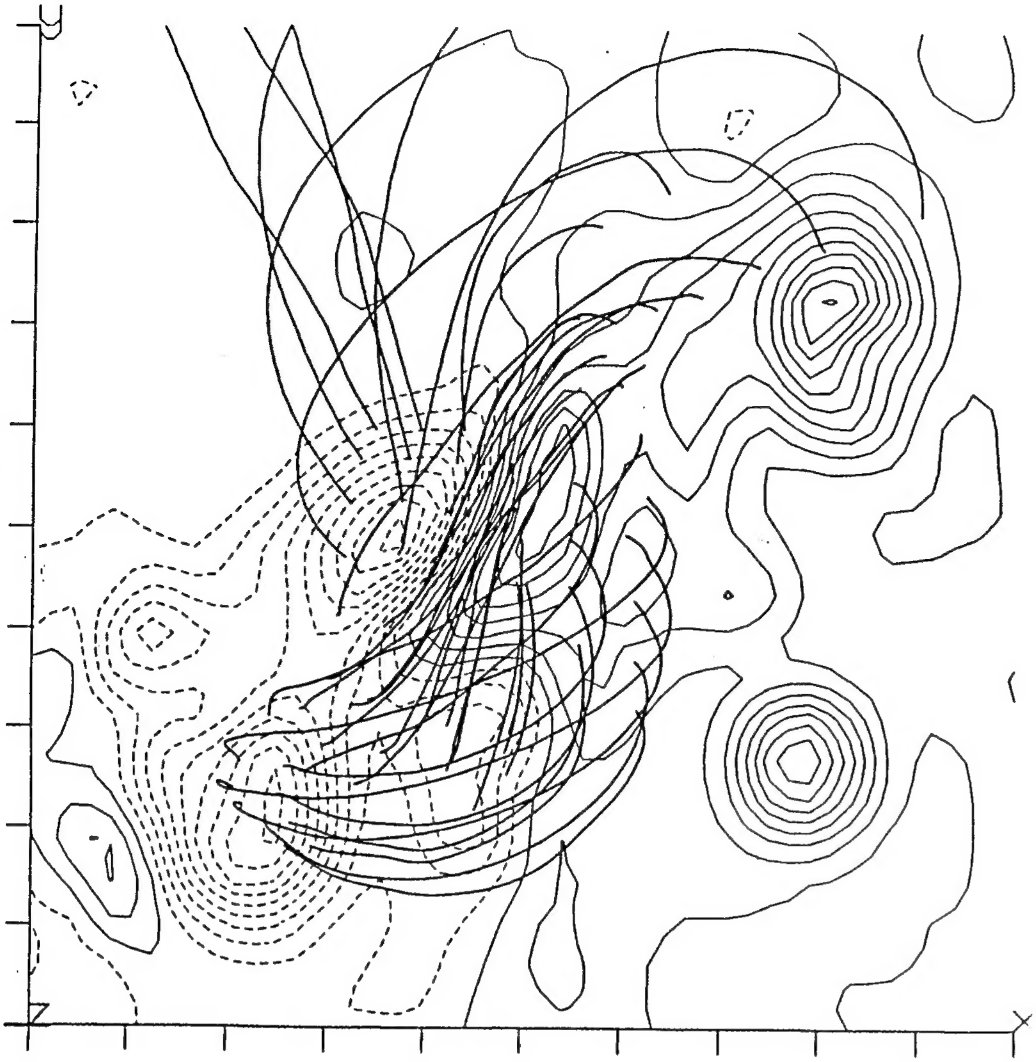

Figure 2(b)

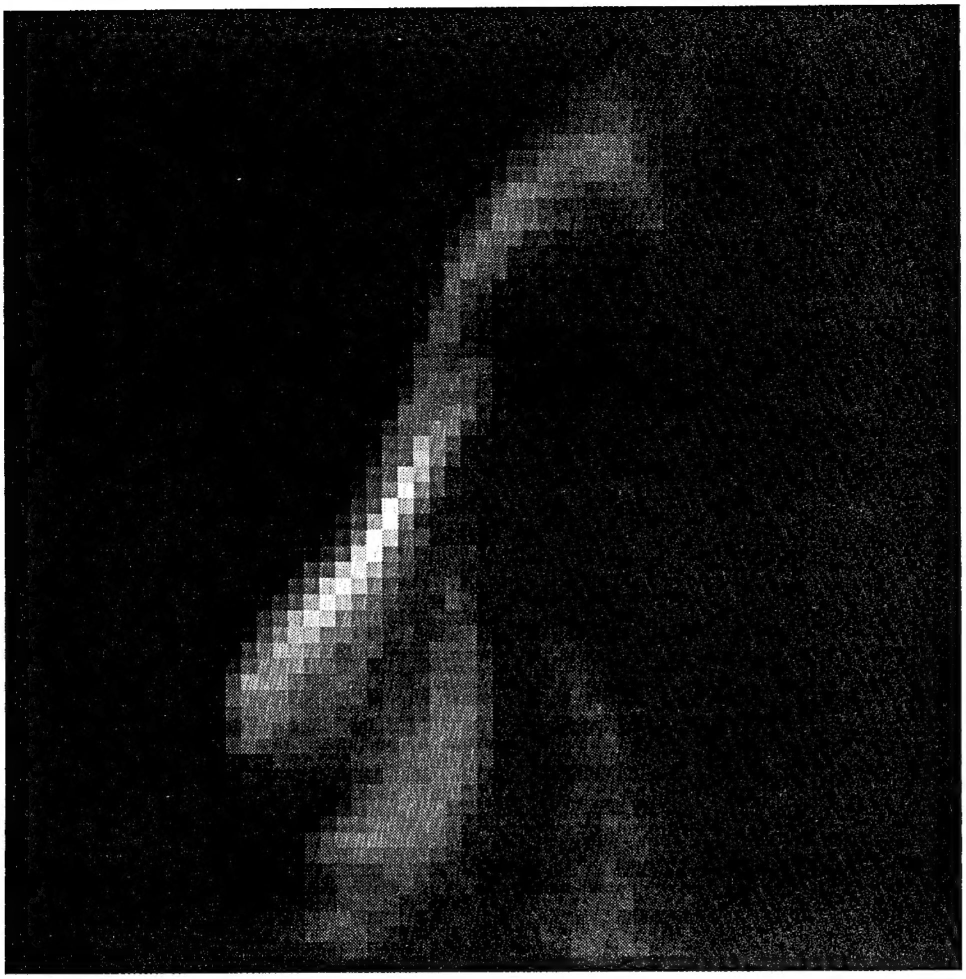

Figure 2(c)

4. Mechanisms of coronal heating

The basic test for whether one understands coronal heating is to construct a model solar atmosphere and compare the properties of the model with observations. The magnetically closed regions of the outer solar atmosphere are usually studied with one-dimensional hydrodynamic loop models. These closed regions include the bright loops that are readily visible in EUV and X-ray images, as well as the fainter, more diffuse plasma that surrounds the Sun. Klimchuk (1992) has reviewed the current state of knowledge concerning static and dynamic loop models and their observational signatures. He summarizes the basic theoretical properties of static, steady-state and time-dependent models, and compares these properties with observations. He concludes that none of the currently proposed coronal heating mechanisms can adequately explain the observational data.

After considering several theoretical possibilities for coronal heating, we have focused our efforts on two promising mechanisms: heating by magnetohydrodynamic waves and heating by magnetic reconnection.

A crucial question is how short period (< 100 s) magnetohydrodynamic waves can be damped in the corona. Lisa Porter, a graduate student who was supported by our Air Force grant, made significant progress towards answering this question as part of her doctoral work (Porter, Klimchuk & Sturrock 1994a, 1994b). Porter derived a very general sixth order dispersion relation for linear magnetohydrodynamic waves in a homogeneous background with a uniform magnetic field. Both compressive ion viscosity and electron thermal conduction are included as dissipation mechanisms, and no assumption concerning the smallness of the damping is introduced. Her work represents a significant generalization of the earlier studies in the literature. The dispersion relation has solutions representing damped fast mode waves. Porter's calculations indicate that fast mode waves can provide adequate energy to heat the quiet corona, but there remains a difficulty in meeting the energy requirements for active regions, where the magnetic field strength is an order of magnitude larger than in the quiet corona.

In the strong-field environment above active regions, it seems likely that magnetic reconnection plays the dominant role in coronal heating. In the reconnection scenario for coronal heating, illustrated in Figure 3, coronal loops are regarded as magnetic flux bundles carrying strong field-aligned electric currents. Photospheric and sub-photospheric convective motions drive coronal loops together, producing a sharp interface containing intense electric currents. A hydromagnetic instability causes the rapid diffusion of magnetic flux across the interface, resulting in the release of stored magnetic energy. The final result of the reconnection process is a dramatic reorganization of the magnetic field lines, with the configuration relaxing towards a current-free, potential state.

Until recently, the reconnection process has never been observed in detail. Roumeliotis (1994) has developed an advanced image reconstruction technique that was applied to soft X-ray data from the Yohkoh spacecraft. Two of the enhanced images, corresponding to the same region at the limb of the Sun viewed five minutes apart, are shown in Figure 4. The first enhanced image resembles the classical picture of two interacting coronal loops

reconnecting at their interface. The second enhanced image shows a relaxed configuration consisting of two well-separated loops.

Roumeliotis and Moore (1993) developed the first self-consistent analytic model of reconnection driven by converging footpoint motions. On the basis of this model, they concluded that it is unlikely that an extended current sheet can be formed by bringing together the footpoints of a quadrupolar magnetic configuration. Instead, electric current sheets must be transient structures that are created during the eruption or sudden internal readjustment of large-scale magnetic field configurations.

We are continuing our work on magnetohydrodynamic waves by modeling the propagation of magnetohydrodynamic waves through a magnetic field whose field lines are stochastically wound around each other. This is likely to be the case for the magnetic field lines above a solar active region, and our initial estimates indicate that mode coupling in such a magnetic environment may lead to the rapid production of slow mode waves which are efficiently dissipated. We are also developing models for the reconnection process in the highly stressed magnetic field configurations which are likely to arise during the eruption and interaction of coronal magnetic structures.

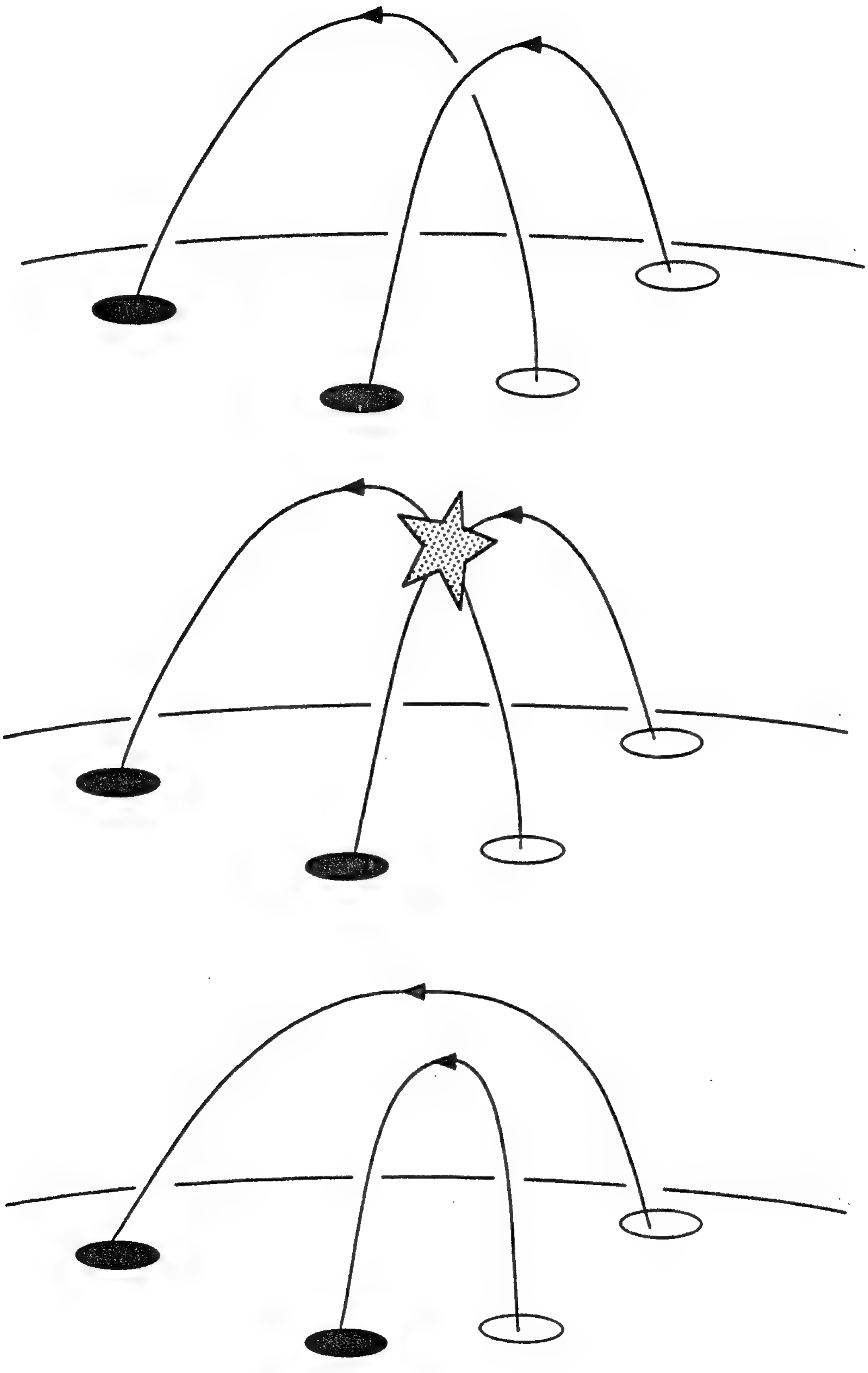

Figure 3

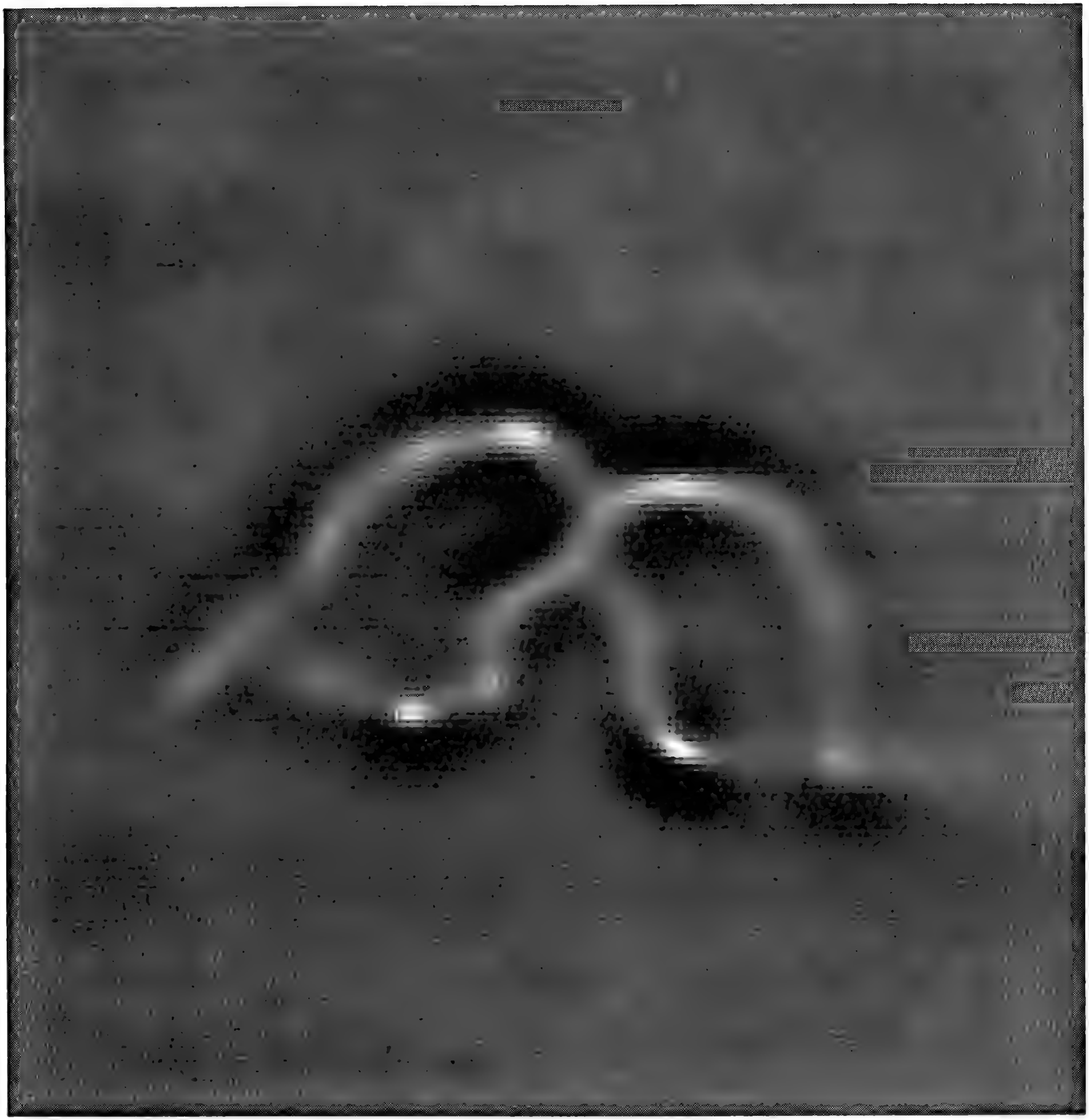

Figure 4(a)

Figure 4(b)

5. Other Topics

Recently, it was discovered by Rieger et al. (Nature, 312, p 623, 1984) that solar flare activity exhibits a periodicity of about 154 days. This discovery was a great surprise at the time. Since then, not only has this periodicity been found in the activity data of earlier times, but also other related periodicities have been discovered. Bai and Sturrock (1991) have recently found intriguing relationships among the periodicities in solar activity that may provide a clue to their origin. In addition to the 154 day periodicity, periodicities of 51, 78, 84, 103 and 129 days have been found from the analysis of various solar activity data for cycles 19 through 22. Because these periods, except for 84 days, are integral multiples of about 25.5 days, Bai and Sturrock have proposed that there is a "clock" within the Sun with a fundamental period of 25.5 days.

In order to quantify the properties of this "clock", Bai and Sturrock (1993) have studied the distribution of major flares in coordinate systems rotating about arbitrary axes with arbitrary periods in the 24.5 to 26.5 range for solar cycles 19 through 22. In this study, Bai and Sturrock have found evidence for two exciters rotating with a period of 25.50 days about an axis tilted by 40 degrees with respect to the ecliptic normal, toward the position of the Earth on December 4. The rotation of these exciters is interpreted as the mechanism that modulates the solar activity.

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